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EARTH STORABLE BIPROPELLANT THRUSTERS FOR GEOSTATIONARY SPACECRAFT

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ABSTRACT

The Liquid Propulsion Systems Centre (LPSC) of the Indian Space Research Organisation (ISRO) has developed and qualified various bipropellant thrusters for use in Geostationary Satellites. The 440 N bipropellant Liquid Apogee Motor (LAM) is used for orbit raising of the satellite and the 22 N bipropellant thrusters are used for Attitude and Orbit Control (AOC) maneuvers.

Increased use of earth storable MON-3/ MMH (monomethyl-hydrazine) bipropellant thrusters in Indian Geostationary Satellites has resulted in new requirements for the development and qualification of a 10N bipropellant thruster for AOC maneuvers. This thruster has been qualified recently and it is under production for future spacecrafts. This paper presents the development and qualification summary and in flight experience of the bipropellant thrusters developed by LPSC.

INTRODUCTION

Geostationary satellites built by ISRO incorporate a unified bipropellant propulsion system utilizing MON-3/MMH propellant combination for orbit raising, station keeping and orbit control maneuvers. LPSC initiated development activities related to bipropellant thrusters for satellite application in the early eighties and the developmental efforts and the solutions found for the problems faced in the initial phase have yielded expertise in the design, fabrication and testing of low thrust engines for spacecraft needs. In house facilities for precision fabrication, clean assembly and environmental testing (including simulated high altitude performance evaluation) have been established. All these engines – 440N, 22N & 10N thrusters have gone through extensive development/qualification testing and have attained a high level of design maturity. This paper summarises in brief the configuration of these thrusters. The extent of qualification testing and the performance achieved are also outlined in this paper.

1.0 LIQUID APOGEE MOTOR (LAM)

The LAM develops a thrust of 440N with a minimum deliverable specific impulse (Isp) of 3041 Nsec / kg_m (310 sec). The mixture ratio of propellants (O/F by weight) is 1.60 ± 0.05,chamber pressure-0.68MPa and the nozzle area ratio is 160. The injector is a coaxial swirl single element and is made of a light alloy. The thrust chamber is made

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of columbium alloy, silicide coated and radiation cooled. The injector assembly is electron beam welded to the thrust chamber. Silicide coating was developed indigenously and the process had been qualified. Coating facilities have been established to cater to the needs of the thrusters for satellites and launch vehicles.The nozzle divergent is also made of Columbium alloy, radiation cooled and silicide coated. Fig.1 shows the LAM assembly. The weight of the engine (including the valves) is 4.0 kg.

[1]The valves used are of the solenoid type with sliding plunger. The valve sealing is achieved by a Teflon seal crimped in the armature loaded against the flat stainless steel seat by a helical spring. The solenoid features dual redundant coils potted and hermetically sealed. A pleated disc filter of 40 micron (abs) is installed at the valve inlet. The valve has an all welded construction.

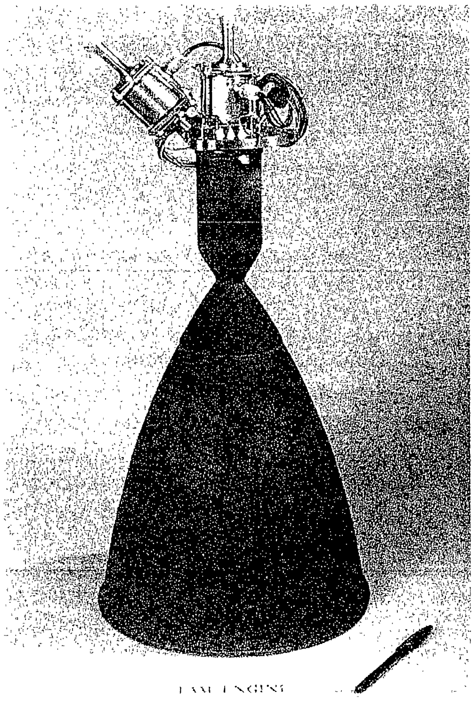

FIG 1: LAM ASSEMBLY

The valves are assembled to the engine mechanically using two seals.The main seal is a face seal of PTFE ‘O’ ring and the other one is a radial seal of Kalrez ‘O’ ring. The thruster valve and the injector flange are protected from the radiant heat generated from the thrust chamber by a heat shield attached to the injector flange.The valves have been subjected to qual. level thermovacuum tests of 6 cycles, each with a lower temp. of -7^0C and higher temp. of 100^0 C and soaking at these temp.’s for 6 hours.The engine assembly has been qualified for the sine and random vibrations.The overall random vibration grms is 16.4 and the sine levels are:

Frequency	Amplitude
5-16	15 mm DA
16-55	20 g
55-100	5 g

Sweep rate : 2 oct/minute

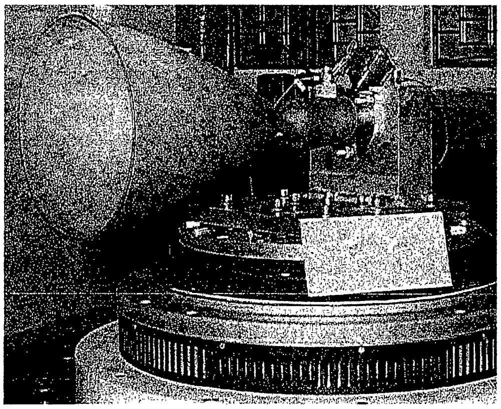

FIG.2: LAM MOUNTED ON VIBRATION TABLE

The development programme was carried out in two phases (1) sea level testing using sea-level engines and (2) High altitude simulation test (HAT) using flight version engine. Sea level tests were mainly to finalise the injector configuration, evaluate the injector performance like C* efficiency, roughness of combustion, transients characteristics, restartability etc. A C* efficiency better than 96 % against the design goal of 95 % and a chamber pressure roughness better than ±4% could be achieved. Three sea-level engines were tested for total burn time of 20,000 sec. One of the sea-level hardware has undergone a cumulative firing of 11700 secs with a single continuous firing of 6000 secs. It has also been tested by varying mixture ratios(1.4 to 2.0) and injection pressures (0.9 MPa to 2.0 MPa).

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The high altitude simulation tests were carried out to verify the steady state and soak back thermal characteristics, specific impulse evaluation and life test in the flight environment. A two stage diffuser ejector system operating with compressed air capable to create a vacuum of 3 mbar during engine firing was used for the HAT. Starting transients and ignition characteristics were evaluated at 10^{-3} mbar using a vacuum pump system. During the HAT development phase,four flight engines were tested for a total burn time of 15,000 sec. One engine was tested for a total duration of 7800 sec with the longest steady state firing of 3000 sec. The longest firing was limited due to the facility constraints. Isp better than 3041 N sec/ kg_m (310 sec) could be achieved and the steady state and soak back temperatures on the valve bodies were much below the specified limits.

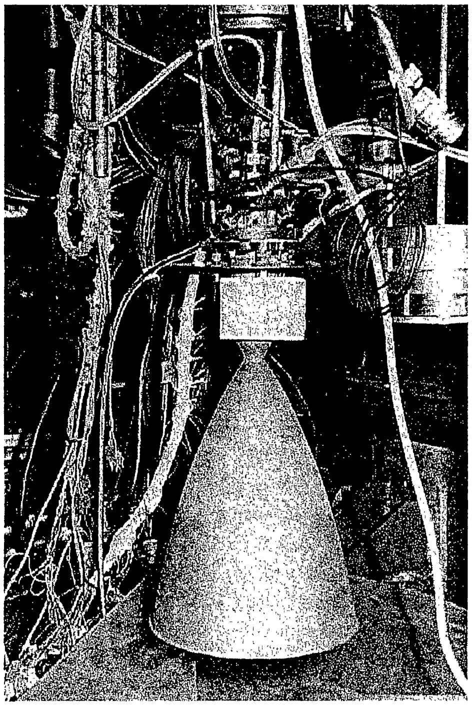

FIG. 3: LAM IN TEST BAY

[2]As part of the qualification HAT programme, five engines were tested and one of the engines was tested for cumulative firing of 24,000 sec with twenty five restarts meeting the mission requirements upto 5 tonne class spacecrafts.Qualification test summary is given in table-1. The engine which had undergone 24000 secs of firing was very much in usable condition and the test was stopped only because there was no requirement more than this duration. The specific objectives of the qual. programme were to demonstrate and document: thruster performance characteristics over a range of operating conditions,the ability of the thruster to withstand the vibrational stresses and maintain the performnce levels after service vibration environment,silicide coating evaluation and thermal restart capability.

Engines	Total burn time in secs	Thermal cycles /restarts	Prop. temp range (Deg.C)	OFF-NOMINAL CONDITIONS	
				Injection. pressure variation (MPa)	Mixture ratio variation
1.	9500	24	-1 to 35	± 0.2	1.42 to 1.85
2.	9544	25	-1 to 62	± 0.2	1.45 to 1.81
3.	9585	23	4 to 67	± 0.2	1.41 to 1.90
4.	9565	16	Ambient	0.2 blow down	1.6 to 2 (blow down)
5.	24000	25	Ambient	±0.2	1.43 to 1.97

TABLE 1 : LAM QUALIFICATION TEST SUMMARY

1.1 Performance and characteristics.

The LAM has demonstrated very good performance for various injection pressures in the range of 0.9 MPa to 2 MPa, mixture ratios in the range of 1.2 to 2 , propellant temperatures in the range of -1°C to 67 °C and supply voltages in the range of 28 VDC to 42 VDC.

Better Isp is obtained for mixture ratios between 1.5 to 1.6. This is due to the fact that with the increase in MR, the injector flange temperature increases resulting in ox. flow path dilation which in turn affects the atomization and combustion efficiency. The maximum temp. of 1200 °C is at the throat region and this is attained within 50 secs of the firing. Outside skin temperature of the combustion chamber near the injector end is less than 300 °C and it is less than 500°C up to the middle of the chamber. Injector flange temperature

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is also well within 200 °C and this temp profile gives a benign condition for the valve steady state and soak back temp enabling it to operate at any restart and varying operating conditions. This temperature gives a sufficiently high margin for the silicide coating life.

1.2 Flight result

[3]LAM performed flawlessly in all the Geostationary satellite missions of ISRO so far. Table 2 gives the on-orbit performance and figure-4 shows the injector flange temp. during one of the missions.

Mission	Longest steady state firing duration (sec)	Total burn time (sec)	Avg. Isp (N-sec/kg$_m$) /(sec)	Max valve soak back temp (Deg C)
1	3529	4740	3061(312)	80
2	3463	5130	3051(311)	96
3	4033	5783	3080(314)	99
4	3605	6729	3090(315)	97
5	3867	5787	3080(314)	80

TABLE-2: LAM ON – ORBIT PERFORMANCE

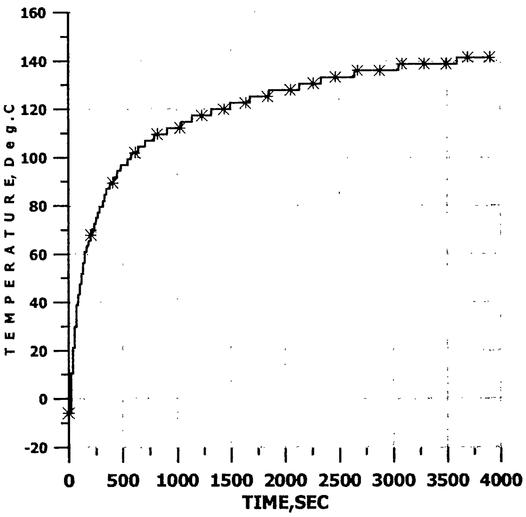

FIG.4 LAM INJECTOR FLANGE TEMPERATURE IN A MISSION

In one of the satellite missions, the operating pressure went up by 0.6 MPa above the nominal value due to an on board technical snag and even under this extreme off-nominal situation for about 3500 sec LAM gave a nominal performance. In another mission due to contingency, LAM was restarted with a time gap of 2 minutes when the soak back temp.'s were at its peak and it performed well.

1.3 Improvements

The specific impulse of LAM can be further increased by 49.05 N sec/kg$_m$ (5 sec) by increasing the area ratio from 160 to 300. The propellant saving due to this for a 2.5 T class satellite is 11 kg and the additional weight penalty of the thruster due to nozzle extension is 400 gm. Design has been completed and drawings finalized. Fabrication will be initiated soon and the first engine firing is expected by the end of this year. Once qualified, this version will be inducted into the future satellites.

2.0 22N THRUSTER

The 22N thruster realized by LPSC also uses co-axial swirl type injector and is made of a light alloy which is electron beam welded to a slilicide coated Columbium thrust chamber. The thrust chamber is radiation cooled and the nozzle area ratio is 100. The engine operates at 0.68 MPa nominal chamber pressure and the specific impulse is 2796 N-sec/kg$_m$ (285 sec) minimum. In pulse mode operation the minimum impulse bit (MIB) obtained is 65 milli Newton seconds for 10 m sec electrical pulse width (EPW). The mass of the engine (including valves) is 0.9 kg. The thruster assembly is shown in figure-5.

The valves are assembled to the injector mechanically using one face seal of PTFE ‘O’ ring and two redundant seals namely Omni seal and Kalrez radial ‘O’ ring. The valves have been subjected to qual. level thermovacuum tests of 6 cycles, each with a lower temp. of -7^{0}C and higher temp. of 100^0 C and soaking at these temp.’s for 6 hours. The engine assembly has been qualified for the sine and random vibrations. The overall random vibration grms is 20.9 and the sine levels are:

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Frequency	Amplitude
5– 18	11.5 mm DA
18– 70	15.0 g
70– 100	8.0 g

Sweep rate: 2 oct/minute

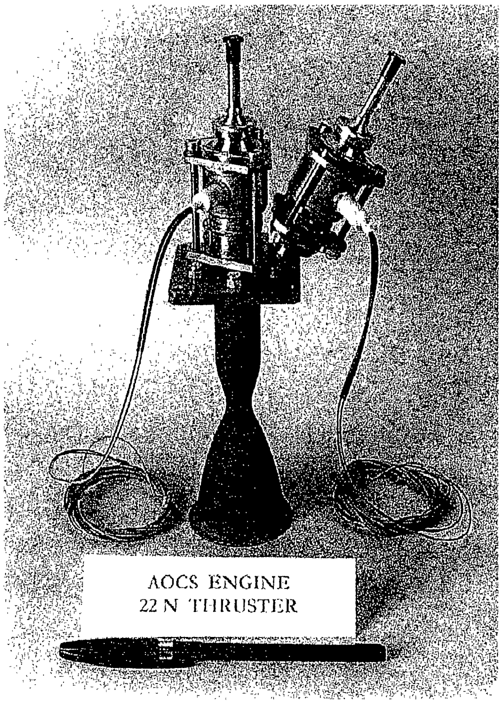

FIG 5: 22N THRUSTER ASSEMBLY

The thruster solenoid valves have plunger type armature and the valve sealing is effected by a Teflon disc in the plunger pressing against a stainless steel seat. All moving elements-armature and the poppet seat assembly are mounted on a set of flexures which provide friction free guidance to the armature, in addition to the seat load necessary for meeting the leak rate specification. The solenoid coil is potted and hermetically sealed. A pleated disc filter of 40 micron (abs) rating is provided at valve inlet and the valve features an all welded construction.

The development tests were of two parts viz sea level and high altitude like in LAM. Five injectors were tested in sea level for about 30,000 sec including 0.3 million pulses and twenty thrusters were tested in HAT for a total burn time of 0.12 million seconds including 2 million pulses.

The final configuration was then frozen and eleven engines have undergone qualification test including qualification level vibration and thermo-vacuum tests.

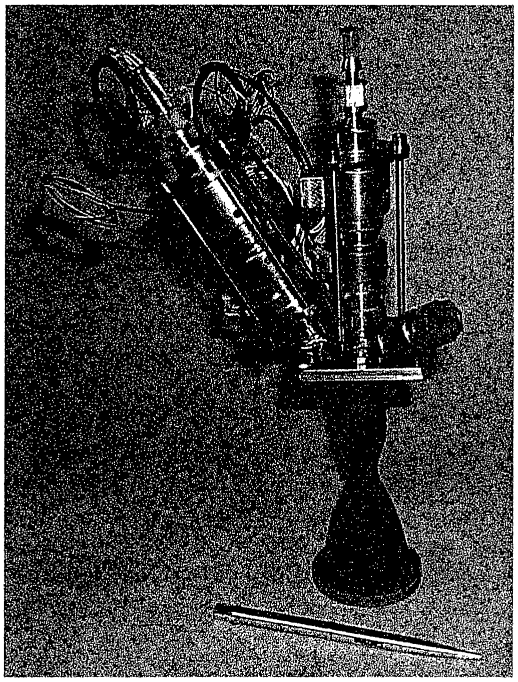

FIG.6 : 22N ENGINE WITH LATCHABLE SERIES REDUNDANT VALVE

[4]The qualification programme comprised testing the thrusters at supply pressures ranging from 0.9 MPa to 1.9 MPa, mixture ratios varying from 1.0 to 2.1, propellant temperatures varying from –1 to 65^0C, valves voltages of 28 to 42 VDC, worst soak-back temperature start, pulse modes of more than thirty duty cycles varying from 0 to 100 percentage etc. A train of 50000 pulses was carried out at the worst case duty cycle to demonstrate the thermal stability of the engine.Valve heating test was conducted by heating both the oxidizer and the fuel valves to more than 70^0C and keeping them at that temperature for 9 days with engine firing in between to evaluate the performance of the engine at elevated valve temperature and compatibilities.Even the valves were heated to 95^0C for 30 minutes and the engine was fired at that temp. to evaluate the performance.Engine could satisfactorily withstand all these extreme temperature conditions.Out of the eleven engines qualified nine were tested for a cumulative

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duration of 14,000 secs each including 0.25 million pulses. The longest steady state firing was 1000 sec as per the mission. One hardware had undergone seven 10,000 sec continuous firing for an accumulated burn-duration of 70,000 secs to demonstrate its capability to operate as LAM back up in the mission in case of contingency. Another engine has completed 225 runs of 150 sec continuous burn to meet North South station keeping maneuver requirements over and above various pulse mode firing of 0.25 million pulses.

2.1 Performance and Characteristics

These engines have been tested extensively for various pulse widths and duty cycles and some of the remarkable characteristics are enlisted below.

- Nominal performance over a wide range of supply pressures, MR's and propellant temperatures.
- Benign operating temperatures provide very large margin for the silicide coating life. Throat is less than 1100 ^{0} C, valve body is less than 60 ^{0} C and injector flange temperature is less than 350 ^{0} C even in worst duty cycles.
- Better pulse to pulse repeatability(± 10%) and engine to engine variation is less than ± 20%and it can give an MIB of 65 m Nsec.
- Operating pressure can be increased or decreased at any stage of the mission as there is no abnormal or thermal runway situation.
- No risk of explosion even when restarted with a time gap after one propellant alone is allowed to flow for some time.
- No thermal runway or performance degradation noticed even after restarting the engine at maximum injector/valve soak back temperature.
- All these tests demonstrated a steady state Isp of 2796 N-sec / kg_m (285 sec)

In short, the thruster has no limitation on any duty cycle and number of pulses and can be restarted at any soak- back temperature.Fig.7 shows the temp. plot in a 10,000 sec test and fig.8 the engine firing in HAT facility.

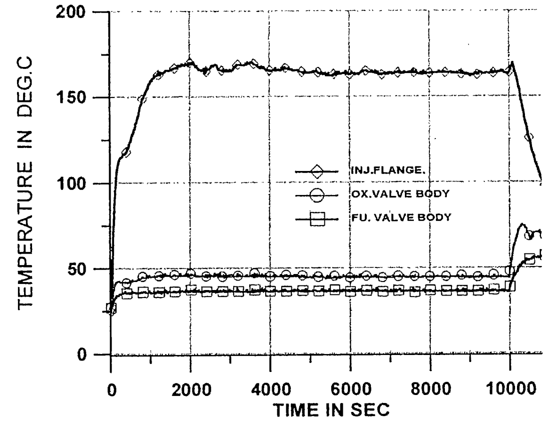

FIG 7: TEMP.PLOT FOR 10,000 SEC TEST

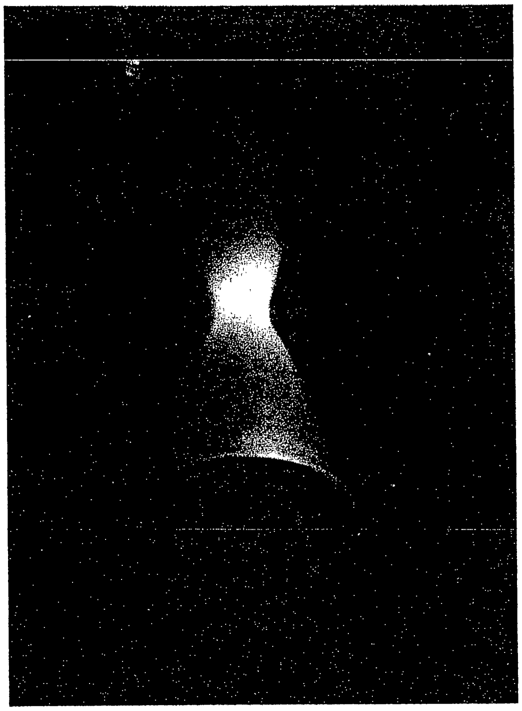

FIG.8: 22N THRUSTER ENGINE FIRING

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2.2 Flight Experience

So far fifty eight flight engines have been supplied and are being used in six satellites. In all the satellites, these engines work extremely well without any operational constraints. Table 3 gives a typical pulse mode firing behaviour of the 22 N thrusters used for attitude hold during apogee motor firings (AMF's)and figure 9 shows the valve body temperature plot during firing.

The above quoted table and graph shows that during firing the thruster valve temp's are less than 30 °C and the soak back valve temp. (maximum) is 80 °C.

Thruster	Duty cycle (%) during AMF- 1
1.	15 %
2.	16 %
3	20 %

TABLE-3

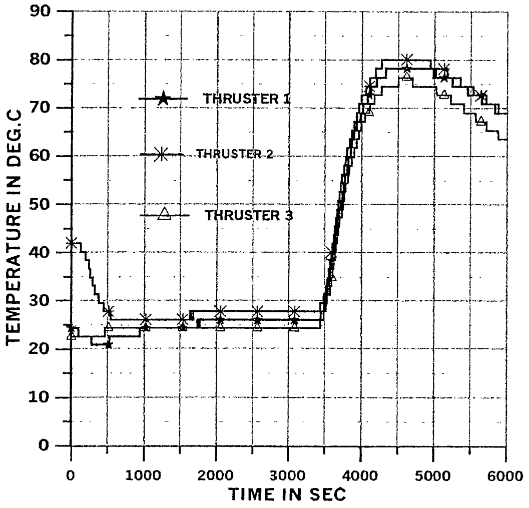

FIG 9: VALVE BODY TEMP DURING AMF-1 IN A MISSION

2.3 Improvements

There was a solenoid operated latch valve kept separately at upstream of the engine control valve in the mission. Now this single seat solenoid operated on-off valve was modified by making the latch valve integral with the on-off valve so that the volume of the propellant between these two valves can be as minimum as possible and also the weight of the propulsion system can be reduced. One engine with the modified valves has been qualified and these are under production for the future satellite. Fig.6 shows the modified thruster assembly with the series redundant valve.

3.0 10N THRUSTER

These thrusters are identical to 22N engine in configuration. Nozzle area ratio is 200 and chamber pressure is 0.68MPa. Solenoid valves (all-welded construction with 40 micron filter) with clapper type armature are used for flow control. These valves can meet the flow requirements of 22N engines also. The figure-10 shows the thruster assembly.

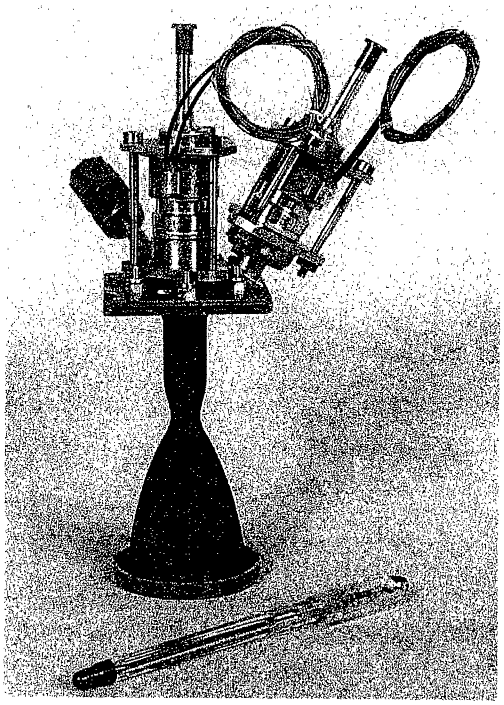

FIG 10 : 10N THRUSTER ASSEMBLY

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The valves are assembled to the injector mechanically using one face seal of PTFE 'O' ring and two redundant seals of omni seal and Kalrez radial 'O' ring. The valves have been subjected to qual. level thermovacuum tests of 6 cycles, each with a lower temp. of -7^{0}C and higher temp. of 100^0 C and soaking at these temp.'s for 6 hours. The engine assembly has been qualified for the sine and random vibrations. The overall random vibration grms is 20.9 and the sine levels are:

Frequency	Amplitude
5- 18	11.5 mm DA
18- 70	15.0 g
70- 100	8.0 g

Sweep rate: 2 oct/minute

This engine also has gone through all the rigorous testing of varying the injection pressures, mixture ratios etc. as that in 22N thruster. This will have better specific impulse of 2845 Nsec/kg$_m$ (290 sec) in the continuous firing as compared to a design goal of 2796Nsec/kg$_m$ (285 sec) and it can deliver an MIB of less than 30 mNsec for 10 msec EPW.

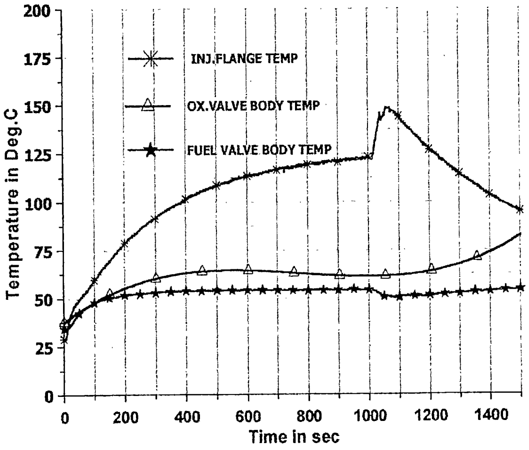

FIG11: TEMP PLOT FOR 1000 SEC TEST

As part of the development effort, two sea-level version engines were tested for a total burn time of 19000 sec.During HAT development three engines were tested. One engine was tested for a cumulative duration of 7045 sec including 40,000 pulses. The other two engines were tested for a total duration of 4750 sec including 41000 pulses. An Isp better than 2845 Nsec/kg$_m$(290 sec)could be achieved with nominal thermal profile in all the development tests.

^{5}HAT qualification was carried out on three engines. Two hardwares were qualified for a total burn time of 19,436 sec including 2.45 lakh pulses. Another engine was hot tested for a cumulative duration of 24,800 sec including 2.52 lakh pulses. As in development test, ISP obtained was 2943 Nsec/kg$_m$ (300sec). The maximum injector flange temp was less than 200 ^{0} C in continuous mode. All other parameters like chamber pressure, flow rates, mixture ratio etc were within limits. In the pulse mode test in the beginning of life (BOL) condition, the MIB for 10 ms EPW is 25 m Nsec.

3.1 Performance and Characteristics

All the characteristics mentioned in section 2.1 of 22N thruster is applicable to 10N.Major differences are: specific impulse is better than 2845 N Sec/kg$_m$ (290 sec) and MIB is better than 30 m N sec for 10 ms EPW. Figure-11 gives the temperature plot (injector and valve body) in a 1000 sec test.

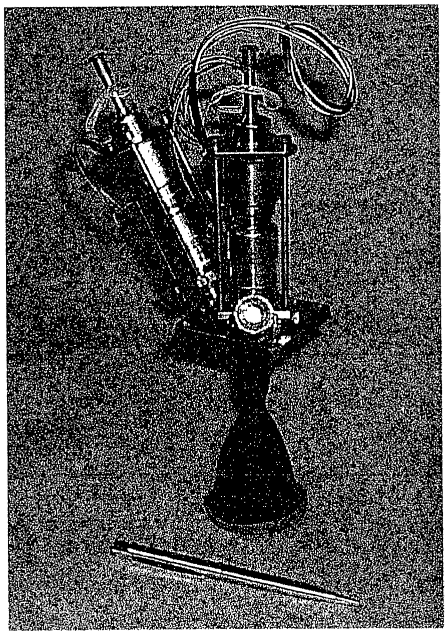

FIG.12: 10 N ENGINE WITH LATCHABLE SERIES REDUNDANT VALVE

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Already eight engines have been delivered for a satellite to be launched this year and these thrusters are under production. For future satellites, the existing flow control valve will be replaced by the control valve assembly with the latch valve located upstream of the solenoid flow control valve as mentioned in section 2.3 of 22N thruster as this valve will be common for both 22N & 10N thrusters. Figure-12 shows the thruster assembly with latchable series redundant valve.

CONCLUSION

The efforts taken by ISRO from the early 80's towards the development of low thrust high performance earth storable bipropellant engines for geostationary spacecrafts have resulted in achieving a high level of design maturity. The utilization of more than eighty such thrusters in the INSAT/GSAT satellites reflects the significant in-house capacity to realize bi-propellant engines in the 10N to 440N thrust range. These thrusters could work satisfactorily even during adverse conditions of high injection pressure and starting at maximum soak back temperatures etc.

Some of the on-going activities in LPSC include the improvement in the specific impulse of the LAM by increasing the area ratio.

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BIBLIOGRAPHY

1. N. Sridharan Dhas, K.L. Valliappan, E.S. Joseph and C.G. Balan, Low thrust engines of ISRO, paper presented at EuroAsian Space week – 22 – 27/11/1998 at International Convention and Exhibition Centre, Singapore,November 1998.

2. S. Venkateswaran, P.Arunkumar, and M. Kanthasamy, LAM qualification test summary, Internal report no. 14/97,May 1997.

3. S.Venkateswaran, P.Arunkumar and M.Kanthasamy, LAM flight performance summary, Internal report no.39/2000,April 2000.

4. Raju.P.Thomas,M.Vinodhakumar,P.Venuprasad and M.N.Prakash, 22N qualification test summary ,Internal report no.40/2000,June 2000.

5. S.Venkateswaran, T.Madhukumar, M.N. Prakash and C.RajeeveSenan, 10N qualification test summary, Internal report no. 41/2000,July 2000.